The Sapir-Whorf Hypothesis And The Meaning Of Quantum Mechanics

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Abstract. In quantum mechanics we have a consistent mathematical structure, but no interpretation in terms of physical images in the classical sense. I question the universal applicability of such images, by arguing that they are products of a classical language. This point of view is in accordance with the Sapir-Whorf Hypothesis, which states that intuition is a product of language, rather that language being an expression of a pre-linguistic intuition. The resulting position is denoted *linguistic empiricism*. This tenet, with the additional assumption that mathematics is a language in physics, is applied to both classical and quantum physics. Some applications of this theory are outlined, mainly in the quantum theory of molecules, and the concept of space.

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INTRODUCTION

In physics, a theory is formulated in terms of a mathematical structure. In classical physics, the mathematical structure can be considered as a formalised representation of a physical content. By physical content w usually mean something that can be imagined, like moving bodies, fluids, or forces. We say that the mathematical structure has a physical interpretation.

The kind of imagination which is used in physics is restricted by what we may call the condition of materiality. What we imagine, we imagine as existing in a three-dimensional space, changing in time. The objects are essentially similar to the objects of our senses, first and foremost the visual and tactile senses, but also the inner sense of strain, which is the elementary experience of a force. Although we may construct abstract concepts, like the four-dimensional time-space or the configuration space of many particles, these are always reducible to the description of basic objects existing at a time at a position.

Quantum mechanics is also formulated in terms of a consistent mathematical structure. In this way it is similar to a classical theory. The strangeness and difficulties appears when we try to understand the physical meaning of this structure. We are confronted with objects which seem to contradict the most elementary demands of material reality.

We can be more precise about this. The strangeness of quantum objects can be summarised by three phenomena: uncertainty, correlation, and non-determinism. Uncertainty, for instance in particle position, seems to indicate that a particle can be several places simultaneously, as long at it is not observed. Correlation or entanglement indicates that two objects have a kind of contact, not created by collisions or forces and which can be more or less independent of distance. Non-determinism implies that even if the conditions given at a certain moment are fully described, the outcome of a process may be uncertain.

The problem is not to accept these phenomena, which we have to, if we want to accept quantum mechanics. The problem is to come to a kind of understanding of what they mean.

To solve this problem it seems appropriate to take as the starting point the satisfactory aspect of the theory, its mathematical structure. This is what I am going to try in this essay. Furthermore, I want to make some assumptions about this structure. I will for instance assume that mathematics is a language, and see where it leads. So, this is the first assumption of this essay: Mathematics is a language.

This contradicts the traditional view, which sees mathematics only as a calculation tool, a system of abstract symbols, some of which can be mapped onto physical quantities. These physical quantities can be and has to be

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described in ordinary language to be meaningful. My assumption implies that the mathematical expressions are themselves linguistic expressions which do not necessarily have to be reducible to ordinary language.

LINGUISTIC EMPIRICISM: THE SAPIR-WHORF HYPOTHESIS

My second assumption is that intuition is shaped by language. This is one way of formulating the Sapir-Whorf hypothesis. Edward Sapir (1884–1939) and Benjamin Lee Whorf (1892–1941) were linguists, who introduced the *principle of linguistic relativism*. The Sapir-Whorf hypothesis states that we think in terms of language, and hence that what we are able to think, experience and imagine depends on our language, its vocabulary and its grammar. They point out that language is more than a tool for reflection and communication; that what we consider as the external real world is built from linguistic meanings. The flux of sense impressions has to be organised by the mind, and this organisation is done in terms of language, concepts and grammatical structures. This conclusion is based on extensive studies of cultures with basically different languages.

Such a position should not be confused with constructivism. It does not imply that we, or our language, construct our experience in any way we like, independent of any external reality. It only means that the external reality can only appear through language, in ways permitted by our language, in terms of the concepts and grammatical structures available in the language. Language is our link to reality, it does not replace reality. Language is not only a restriction. It also opens up the reality to our experience and imagination, although, at the same time, it limits the possibilities of these faculties.

The Sapir-Whorf hypothesis also allows for influence in the opposite direction, that language is influenced by the external reality. This reality does not present itself outside language, but it makes an impression on language, it constrains the way a valid language can be.

Such a position can be denoted *linguistic empiricism*. This is the position I am suggesting.

Physics is based on experience, or more precisely: on perception. This is the basic, self-evident assumption of any working physicist. The implications of this assumption have been investigated philosophically under the labels of empiricism, pragmatism and phenomenology. Edmond Husserl (1859–1938), the founder of phenomenology, has pointed out that a perception is *constituted* in a process where the subject is active. Thus, a perception is not simply a passive reception of sense impressions from the outside; it is, at the same time, an act of interpretation. The Sapir-Whorf hypothesis implies that in this act language plays a crucial role.

This assumption has implications for all of physics, including classical physics. It means that even the everyday phenomena dealt with by classical theories are not as elementary and universal as they appear to be. For instance, our notions of a liquid, of its pressure and flow, are precisely that; notions, concepts, established in our minds through a combined process of sense experiences and language acquisition. The same applies to the various concepts of space, which we will consider later. Or experience with and observations of such phenomena depend on the language which penetrates into the observational process.

This role of language is for the most part invisible to the language-user. It is the nature of language to hide its own effect. The ideas or meanings established through the constitution of words and grammatical relations in a language appear to the language-user as independent existents, as obvious categories.

This linguistic aspect of experience carries over to our imagination. The inner pictures created in our minds are shaped by the conceptual meanings of our language. It may be fairly obvious that rational reasoning and analysis depends on language, but this assumption is stronger. It implies that what we call physical intuition is not a faculty independent of and prior to our use of language. Our intuition is constituted by linguistic elements, it is shaped by language. However, it is shaped by a language which itself is created in the interaction of human consciousness with the flux of sensations bringing us in contact with the outside world.

The assumption that language shapes our intuition is a radical one. Although the history of physics demonstrates its validity, it is not easy accept. It may be fairly easy to agree to that the concepts that I use to today in understanding the universe are incompatible to concepts that have been used at earlier times or in other cultures. It may also sound reasonable that this conceptual development has lead to a change in ways of thinking and imagining things, that is, that my intuition is different from that of a person living, e.g., in the thirteenth century. But it is much harder to imagine that my own intuition may be limited and inadequate in dealing with phenomena outside reach of my language.

As I have pointed out, the effect of language is usually invisible to its user. However, in some situations, at some critical stages of the development of science, it comes to the surface. This is when the inappropriateness of a concept becomes a recognisable obstacle to a further development of a scientific theory. One such example is the modification of the concept of space which we find in the development of Einstein's theories of relativity. The Newtonian concept of absolute or abstract space made progress towards these theories difficult. Thus, Einstein had to do more than to study observations or developing mathematics. He had to pay attention to the physically concepts which were in current use, and how they shaped the intuition of his contemporaries. He even had to reconsider the most basic of all ideas implied in the condition of materiality, namely the concept of space. In this process, he had to bring to the surface the implied meaning commonly associated with the concept in his times. And he noted that the relativity of space was overlooked, due to the habitual and unconscious reference to the earth as a reference system[1]. This famous example illustrates the interdependence between language and intuition.

FORMAL MATHEMATICS IS FORMAL GRAMMAR

Before I proceed to the study of mathematics as a langue, I would like to make a digression and point out one noteworthy effect the extensive usage of mathematics in physics may have; an effect which contributes substantially in hiding the linguistic nature of mathematics to many physicists. Again, we may use the theories of relativity as example. As long as one tries to understand Einsteinian relativity in terms of words, one is forced to reconsider notions and ideas which are parts of our inherited language and thinking habits. However, Einstein's theories of relativity do not only consist of a new conceptual structure; they are also systems of abstract mathematics. It is therefore possible to be a very competent user of these theories without really understanding their physical meaning. There are probably many physicists with an impressive mastery of the general theory of relativity who are unable to explain the revolutionary concept of space on which it is built, and which Einstein so scrupulously lays out in his works. There is something about the abstractness of mathematics, its general applicability, and the flexibility of mathematical notation that makes it easy to overlook the fact that mathematics, too, is a language in physics. I will try to explain why.

Mathematics has a very rigorous structure. This rigor makes it possible to do a lot of physics in a formal way, without thinking too much about the physical meaning of the variables and equations involved. This phenomenon, that the handling of mathematics is independent of its possible physical meaning is, however, a general linguistic phenomenon which can be found also in ordinary language when reasoning in terms of grammatical structure.

Let us take an example. We consider two sentence forms: "Everything that is an A is also a B" and "x is an A". From this we can conclude that "x is a B". We may, for instance, say that every animal with six legs are insects. We may furthermore say that a fly has six legs. And, from these facts we conclude that a fly is an insect. It is a valid conclusion, but it is more than that, it is meaningful speech. We understand what is said.

We could instead make the rather strange assumption that every *flott* is also a *bil*. Furthermore, from the equally unintelligible information that a *hest* is a *flott*, we conclude without difficulty that a *hest* is a *bil*. We can make this conclusion without the slightest notion of what the words *flott*, *hest*, or *bil* mean.

The same applies to mathematical derivations in physics. And, to a certain extent, this effect can explain that we can use quantum mechanics comfortably without being disturbed by its apparent lack of intuitive content. As long as we are doing engineering, this works fine. The practical ability of using the theory is all we need. However, if physics is a means for understanding the universe, it is highly unsatisfactory. So, what should we do about it?

What we should do is to accept mathematics as a language, and not only as a formal structure and a tool for calculation.

THE WEB OF MEANING

What would be the implications of such a view? One important consequence can be explained thus. If you consider mathematics only as an abstract formalisation, one has to identify certain objects of the mathematical structure which can be mapped onto certain physically explainable entities. Only these entities have physical meaning, the rest is abstract formalism.

However, a language works differently.

Let us again take an example. Let us, in the honour of Schrödinger, consider a cat; a black, friendly cat. The property of being black is easy to deal with as a physical property. It can be observed by physical instruments. It is like the properties of quantum mechanics corresponding to self-adjoint operators. But then we consider the property of being friendly. This property can be described as a complex of possible responses on a variety of situations. Each such response may be reduced to physically observable patterns of motion, although it will probably be more complex to observe than the measurement of colour. But the property of friendliness is more than this set of responses. These responses makes a common meaning, they build up a cognitive unity or gestalt, a property we can understand as such without specifying all responses it implies. Such is the sophisticated work of language; we are able to build meanings on meanings in incredibly complex patterns.

If we look at the mathematics of quantum mechanics as a language, complex meanings are developed in an analogous way. One cannot maintain the traditional assumption that only quantities corresponding to self-adjoint operators are physical. One such example of a more complex but equally meaningful entity is the wave function.

There are wave functions or probability amplitudes corresponding to all self-adjoint operators of the system considered, but let us simplify the discussion by considering only the one corresponding to position in space. It is true that the probability amplitude determines the statistics of position observations. It is also true that the wave function contains more information than this, for instance by its sign.

The wave function also gives rise to other properties, like the electron density of a molecule. The electron density, mathematically the diagonal reduced density matrix of the electron system, is a physically and chemically very important property of a molecule. It is indirectly observed in the interaction pattern between molecules, for instance in the bonds between water molecules in liquid water.

In an ordinary language we also find the analogue of an approximation in physics. The friendliness of a cat will usually be established in spite of its behaviour towards mice, or generally what is accepted as reasonable exceptions. Tolerance towards exceptions is the simplest example of an approximation, and shows that approximations may be necessary to establish a concept at all. But there are examples of concepts where the introduction of approximations is even more essential to their establishment.

One example is when we talk about the intentions of a nation, which may have peaceful or aggressive intentions. Now, an intention is something that characterise a human individual. So, here we have a problem in understanding the basis for the concept of a nation's intentions. We may construct formal definitions. For instance, we may say that, by an intention of the country I mean …, for instance the common intentions of the majority of the parliament, or simply the intentions of the president. But if we try to retrace how the concept of a nation's intentions is established, it is not through formal definitions. It is more correct to say that we see the nation in the image of a human being, think of it to a certain extent as if it was a human being with an individual will. This way of simplifying our image of very complex phenomenon is used all the time in a language. And here we have an essential approximation, which makes a new idea or concept possible, the idea of a nation's intention. After having established this idea, we can use it in a comprehensive and scientific analysis of the behaviour of the nation to try to determine if its intentions are peaceful or aggressive.

In the quantum description of a molecule as applied to chemistry a series of approximations are applied. Some of them are straightforward, like when we assume the nuclei and the electrons to be being point-like, or when we use the non-relativistic Schrödinger equation. An example of an essential approximation is the Born-Oppenheimer approximation, which gives rise to the idea of a molecular geometrical structure. Furthermore, there is the approximation of introducing single electron- or electron-pair wave functions or orbitals, neglecting electron correlation. This gives rise to concepts like valence electrons.

Observations are almost always interpreted in terms of approximate models. One interesting example in chemistry is the scanning tunnelling microscope, which, to the first approximation, observes the density of the valence electrons on a solid surface.

Another interesting example, taken from my own research, is the interpretation that X-ray diffraction on solids measures the form factor, and hence, indirectly, the electron density. I have demonstrated that this is no longer the case if one includes the first order relativistic correction to the electron part of the scattering model. The quantity which is measured in this refined approximation is more complex, but could be given a name.

There are also processes where the amplitude, not only the density, of the valence atoms of molecules is observed indirectly. Not in numerical detail, but in a way such that the sign of the amplitude is essential. This is in chemical reactions. This is most clearly demonstrated in the Woodward-Hoffman rules of pericyclic reactions. Here one can use very simple approximations for the orbitals, but the sign is essential in determining the possible reaction paths. Thus, by observing the reaction products, one is indirectly observing some qualitative aspect of the wave function which can not be replaced by densities and which does not correspond to self-adjoint operators.

Then, consider a different example. Let us walk in Einstein's track and once more question the notion of space. Let us take the mathematical language of quantum mechanics at face value and ask what it says about space.

The common view of space as we experience it is according to the Newtonian view. This is what Einstein calls "abstract space", because it exists in itself and is not conceptually tied to the notion of a solid body. To Einstein, space is a possible extension of a solid body. An extension can be realised by moving another body into that area of space. This is a transformation. Thus space is the possibility of a transformation, and the dimension of space is the dimension of the parameter space of the system of possible transformations.

The transformation concept of space carries over to quantum mechanics without difficulties. We say that the Hilbert space corresponding to a particle carries a representation of the Galilean group of transformations, in the non-relativistic case, or else, the Poincaré group. So, even if a particle is not precisely located in space, we can transform its description from one system of reference to another in a way analogous to that of classical mechanics.

However, the Newtonian and the Einsteinian space have in common that solids are precisely located relative to one another. Such is not the case in quantum mechanics, except for some limiting states. Thus, we need to replace the notion of localisation with other notions from the language of quantum mechanics, i.e. from its mathematical structure. And here we have a rich variety of descriptive notions; all derived from and related to the wave functions.

My conclusion may be formulated thus.

Our basic conceptions of matter, with bodies and fluids moving in space and time, are not inevitable primitive given notions, but are products of a process of interpretation and language development in a society without any experiences of the kind dealt with by quantum mechanics.

An educated physicist has modified and extended this habitual way of interpreting tings. But this extension has been too slight to disclose the general fact that intuition as such is dependent of language and its implicit theories.

By treating mathematics in physics as a formal system of logical rules, its epistemological and linguistic possibilities have not been fully explored by the physicists. Hence we have got the notion of "mathematical formalism".

To develop an intuition and a faculty of imagination adequate for the quantum reality, one has to build on the mathematical structure applied as a language, with all its complex meaning-generating power. There are no purely mathematical entities in the quantum mechanics, as opposed to empirical entities. The web of meaning sweeps throughout the theory.

DERRIDA AND WRITING

At the beginning of this essay, I presented the Sapir-Whorf Hypothesis. This hypothesis can be underpinned and developed further by taking into account the contributions of Jacques Derrida (1930–2004). Derridas philosophy of language and its relation to experience[2] cannot be condensed into few sentences, but I would like at the end to indicate some of its basic ideas. We may ask why language is of such importance, why our linguistic structure is at the basis of all experience and imagination. Three key words are *sameness*, *repetition*, and *recognition*. If a sensual encounter with the external reality is to be counted as an experience to which we can relate intellectually, and from which we learn anything, we have to be able to repeat it in our mind. In science one has the demand that an experiment has to be repeatable in principle. However, this idea presupposes the possibility of identifying two experiments as the same, thus we have to have the more basic notion of recognition. More generally, the constitution of a perception as meaningful also presupposes an experience of recognition. These basic notions are elements of stability in the flux of sensation, and language is the tool for establishing this stability. And, as Derrida points out, it means language also in the physical sense, with its sounds and graphic images.

In ordinary language this points to the importance of how language is used, the selection of words and linguistic expressions. In physics it points to the importance of mathematical notation and choice of representation. Many physicists have had the experience of understanding quantum mechanics more deeply when learning the Dirac notation. It is not just a question of aesthetic enjoyment, it is something deeper, something which every author knows and which every physicist should be aware of: the amazing and almost mystical connection between understanding and writing.

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